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Physics Issues Related to the Confinement of ICF Experiments in the U.S. National Ignition Facility*

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Abstract. ICF experiments planned for the proposed US National Ignition Facility [NIF] will produce emissions of neutrons, x rays, debris, and shrapnel. The NIF Target Area [TA] must acceptably confine these emissions and respond to their effects to allow an efficient rate of experiments, from 600 to possibly 1500 per year, and minimal down time for maintenance. Detailed computer code predictions of emissions are necessary to study their effects and impacts on Target Area operations. Preliminary results show that the rate of debris shield transmission loss [and subsequent periodicity of change-out] due to ablated material deposition is acceptable, neutron effects on optics are manageable, and preliminary safety analyses show a facility rating of low hazard, non-nuclear. Therefore, NIF Target Area design features such as fused silica debris shields, refractory first wall coating, and concrete shielding are effective solutions to confinement of ICF experiment emissions.

Introduction

The repeated confinement of ICF experiments producing yields up to 20 MJ in the proposed US National Ignition Facility introduces unique challenges. The per shot increase in laser energy between NIF and the existing Nova laser facility, for example, is a factor of 40, while the increase in total yield will be 10^5 . Two of the unique challenges are understanding the characteristics of target emissions (neutrons, x rays, debris, and shrapnel) and their effects on materials; and designing a facility that will meet both stringent environmental standards and an acceptable experiment rate, both for reasonable capital and operational costs.

Here we summarize the results of primarily radiation-hydrodynamics code calculations that predicted NIF target emissions of x rays, debris, and shrapnel as a function of fusion yield, including considerations of two-dimensional effects such as debris jetting and Lambertian x-ray emission. Predicted responses of first wall materials (a refractory material such as plasma-sprayed boron), the debris shield, and the tip of the target positioner is presented, including characteristics of

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the heated material (vapor, melt, spall, etc.), as well as the consequences to NIF operations.

We also discuss the work-in-progress in experimentally assessing the degradation in optical transmission of fused silica and KDP due to neutron and γ -ray deposition. The specific impacts of *pulsed* neutron and γ -ray irradiation and spectral dependence is discussed.

NIF has received a preliminary safety rating as non-nuclear, low hazard. Public dose and occupational exposure are restricted through shielding and the use of low activation material (aluminum). From an environment and safety perspective, the facility site can accommodate individual yields ≤ 45 MJ and an annual total yield of ≥ 2000 MJ, enough to encompass the expected demand for access to NIF.

NIF Target Area Design Overview

Prior to a shot, the target area must provide target chamber vacuum, and a stable platform for the target and its diagnostics. During a shot, the impact of the energy introduced into the chamber must be mitigated, and workers and the public protected from prompt radiation. Careful material selection controls residual radioactivity to allow required accessibility. Tritium and other radioactive wastes are collected and disposed. Diagnostic data is also retrieved, and the facility is readied for the next shot.

The 5-m radius NIF target chamber, made from Al 5083, is 10-cm thick. The target positioner inserts targets at the chamber 'waist' and laser beam ports are positioned in two concentric cones (27° and 53° , top and bottom). The final optic, a fused silica debris shield, is 6.75 m from chamber center. [see Fig. 1](1)

The NIF chamber and target area support structures become radioactive following shots producing neutrons. Shielding on the chamber exterior [~ 40 cm of borated concrete] reduces activation of structures as well as reduces the dose from the radioactive decay of the chamber. Controlled/monitored access to the chamber area is required for hours to several days after shots producing neutrons, depending on the yield. The target chamber support structure is made from aluminum-reinforced, borated concrete to provide stability *and* minimal radiation levels with reasonable cost. NIF's design lifetime is 30 years. A possible annual shot 'mix' is shown in Table 1. Designing to this shot envelope will ensure adequate facility flexibility.

Table 1. Assumed annual NIF target experiments for design purposes

Laser Energy (MJ)	Number of shots	Target Yield (MJ)
1.0	225-600	0
1.5	225-600	0
1.8	150-300	0.1 - 20 MJ
	100-250	0.1 MJ
	10-50	20 MJ

ICF Target Emissions and Their Effects

To repeatedly confine NIF fusion experiments, the pressure pulse from the target must be well contained, debris shields must remain at $\geq 97\%$ transmission by avoiding surface contamination, and neutron activation must be maintained at acceptable levels. A quantitative treatment of the threat to the debris shields requires an understanding of target emissions and materials responses.

X rays

X-ray and debris emissions were calculated for seven fusion NIF target yields [0.45 to 30 MJ] with a 1.8-MJ laser drive using the code LASNEX in one-dimension (2). The target was modeled as shown in Figure 2 but without the cryogenic support system (e.g. hohlraum only). A 'leak source' was used to model the laser entrance hole, revealing some two-dimensional features to the emission, such as the relative fraction of x-ray energy emitted from the hot hohlraum wall as opposed to the laser entrance hole. A Lambertian (cosine) distribution of radiation from the laser entrance holes is assumed. The results are listed in Table 2.

Debris

Debris is shown in Table 3. The effects of debris jetting have been observed on Nova. We postulate debris jetting with a 37° half angle, as this is consistent with other two-dimensional calculations done to examine this issue.(3) The mass involved in the jet is inferred from the mass of inward and outward moving material from the LASNEX calculation. The pulse length is determined by the range in material velocity for a given case.

Shrapnel

Shrapnel generation calculations show that more than five million few-micron average size droplets reach velocities of ~ 1 km/s for a 20-MJ yield.

X-ray Effects

The target positioner will be protected with a frost-coated plate, where the frost [likely water] will condense from the $\leq 10^{-6}$ Torr chamber vacuum by a cryogenically-cooled panel. Despite several hundred microns of frost removal, no deposition on the debris shield from the positioner is expected since only a non-condensable gas is produced. The first wall surface, likely a boron-based plasma spray material, will be exposed to the x-ray and debris fluences listed in Tables 2 and 3. For a 20-MJ shot, we estimate 120 g of thermal spray coating to be removed, possibly depositing ≤ 0.2 μm on debris shields. This is done by calculating an energy deposition profile in the material due to the absorption of the x-ray fluences and spectra shown in Table 2. Photon interaction cross sections

Table 2. X-ray fluences and other characteristics of NIF x-ray target emissions.

Shot Energy & Fusion Yield (MJ)	X-ray energy (MJ)	~BB Temp (eV)	Pulse (ns)	Target Positioner Fluence (J/cm ²)	Peak 1st Wall Fluence (J/cm ²)	Peak Debris Shield Fluence (J/cm ²)	#/year
≤ 1.5	≤ 0.59	60% ≤ 260	≤ 10	0	≤ 0.22	≤ 0.12	450-1200
		40% ≤ 34	≤ 61	≤ 190	≤ 0.08	≤ 0.04	
Total				≤ 190	≤ 0.30	≤ 0.16	
1.8	0.68	60% @ 260	9.9	0	0.26	0.13	150-300
		40% @ 34	61	217	0.09	0.05	
Total				217	0.35	0.18	
100 kJ	0.70	60% @ 260	9.8	0	0.27	0.13	100-250
		40% @ 34	62	223	0.09	0.05	
Total				223	0.36	0.18	
20 MJ	4.23	40% @ 400	6.3	0	1.07	0.52	10-50
		14% @ 150	49	469	0.19	0.10	
		46% @ 47	49	1558	0.62	0.34	
Total				2028	1.88	0.97	

are taken from the LLNL Evaluated Photon Data Library.(4) For conservatism, we assume all material at or above the incipient melt energy density is removed. The target assembly will deposit ~0.5 Å of material on the debris shield each shot. Total deposition in one week *before* a 20-MJ shot is a few Å. Therefore, weekly changeout of each debris shield is planned.

Debris Effects

Although the debris loading is a large total energy fluence, the power is low enough due to long deposition times that thermal conduction effects result in no material being ablated.

Shrapnel Effects

For a single 20-MJ shot, approximately 3% of the area of the inside of the chamber in a band near the centerline is pitted.(3) Although shrapnel will ultimately degrade the NIF debris shields due to pitting, we expect ablated material deposition to be the most stressing area. When debris shields are removed for cleaning, any shrapnel damage can be repaired at that time.

Table 3. Debris fluences and other characteristics of NIF debris target emissions.

Shot Energy & Fusion Yield (MJ)	Debris Energy (MJ)	Average Velocity (cm/ μ s)	Target Positioner Fluence Mass Pulse	Peak 1st Wall Fluence Mass Pulse	Peak Debris Shield Fluence Mass Pulse	#year
≤ 1.5	≤ 0.40	≤ 8	188 J/cm ²	0.33 J/cm ²	0.18 J/cm ²	450-1200
			104 μ g/cm ²	68 ng/cm ²	38 ng/cm ²	
			1.35 μ s	67 μ s	91 μ s	
1.8	0.44	8	207 J/cm ²	0.37 J/cm ²	0.20 J/cm ²	150-300
			104 μ g/cm ²	68 ng/cm ²	38 ng/cm ²	
			1.35 μ s	67 μ s	91 μ s	
100 kJ	0.46	8	216 J/cm ²	0.39 J/cm ²	0.21 J/cm ²	100-250
			104 μ g/cm ²	68 ng/cm ²	38 ng/cm ²	
			1.35 μ s	67 μ s	91 μ s	
20 MJ	1.85	16	916 J/cm ²	1.46 J/cm ²	0.80 J/cm ²	10-50
			93 μ g/cm ²	87 ng/cm ²	48 ng/cm ²	
			1 μ s	50 μ s	68 μ s	

Neutron Effects

The neutron and γ -ray dose to the debris shields is calculated to be ~ 2 krad due to neutrons and ~ 1 krad for neutron-induced γ -rays, for a single 20-MJ NIF yield. Therefore, a total NIF lifetime dose could range from ~ 2 to 9 Mrad. Previous exposures on RTNS-II indicated that SiO₂ did not experience any significant degradation until approximately 20 Mrad total dose. We also find that ~ 300 krad reduces the transmission of fused silica by $<1\%$ at 3ω . An experiment to investigate whether the short-pulse NIF fluence might cause more damage than the continuous testing fluences was conducted on the Sandia Pulsed Reactor III. For equal doses of radiation [400 krad γ -ray/160 krad neutron], delivered over a period of 30 minutes for some samples and in four 100 μ s pulses over 30 hours for others, the samples exposed to the higher flux actually exhibited less reduction in transmission. Further investigations using the LLNL ⁶⁰Co source revealed that fused silica with as-manufactured no-oxygen deficiency is very hard to γ -ray irradiation. Fused silica has a potential advantage over fused quartz due to this

issue. However, *after* neutron irradiation, fused silica shows susceptibility to γ -ray damage. This is due to oxygen displacements, creating oxygen-deficient centers for color center damage to accumulate. The oxygen deficient color center is 246 nm. Fortunately, the 246 nm line is transmuted to 210 nm by the subsequent γ -ray radiation. KDP appears at least as damage resistant as fused silica, although controlling impurities is now known to be a key issue for making KDP hard to radiation damage. Further investigations will explore the effects of the spectral differences between the SPR-III fission source and NIF where the damage is mainly due to 14 MeV neutron deposition. An important difference between the two spectra is average γ -ray production cross section. The value for 14-MeV is about 10^3 greater than for a fission spectrum. Predictions of the impact of NIF operations on optical performance can be made when the study is completed.

Environment and Safety

The NIF project is considering expanding the annual shot envelope from 385 to 2000 MJ per year. Recent environmental analyses indicate that the increased annual yield would result in a site boundary dose only 15% higher [0.15 mrem vs. 0.13 mrem]. Additionally, increasing the largest single shot yield [for environmental considerations] from 20 to 45 MJ results in a *lower* accident site boundary dose. This dose is substantially due to activated air emissions. The reduction is due to accounting for the elevated release height and mixing with fresh air, aspects ignored in previous analyses. The result is a reduction in dose to an individual at 30m, from 2.7 rem to < 0.025 rem. The significance is the NIF facility non-nuclear rating is based on the dose at 30-m staying below 10 rem. These analyses show that instead of being within a factor of ~ 3 of a possible nuclear rating, NIF is more than a factor of 100 away.

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